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Hattersley

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- (54) **MAGNETIC PROBE APPARATUS**
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(56) **References Cited**
U.S. PATENT DOCUMENTS

2,614,164 A 10/1952 Huston
3,445,928 A 5/1969 Beynon
(Continued)

FOREIGN PATENT DOCUMENTS

DE 29724862 3/2005
DE 102007009016 8/2008
(Continued)

OTHER PUBLICATIONS

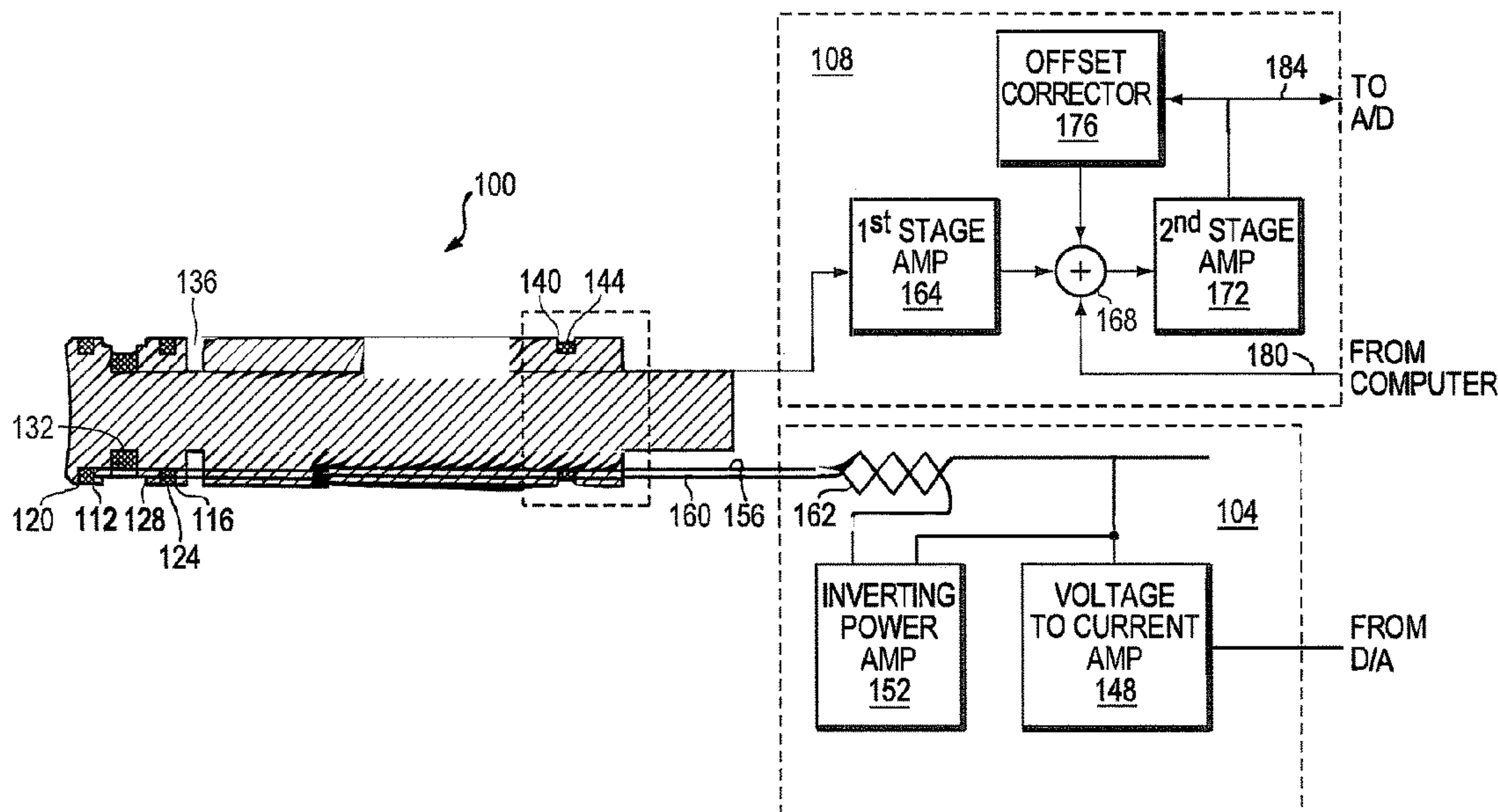
English translation of Office Action for Japanese Patent Application No. 2008-508306, dispatched in Nov. 8, 2011, 6 pages.
(Continued)

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(57) **ABSTRACT**

A system and method for locating magnetic material. In one embodiment the system includes a magnetic probe; a power module in electrical communication with the magnetic probe to supply current to the magnetic probe; a sense module in electrical communication with the magnetic probe to receive signals from the magnetic probe; and a computer in electrical communication with the power module and the sense module. The computer generates a waveform that controls the supply of current from the power module and receives a signal from the sense module that indicates the presence of magnetic material. The magnetic probe is constructed from a material having a coefficient of thermal expansion of substantially $10^{-6}/^{\circ}\text{C}$. or less and a Young's modulus of substantially 50 GPa or greater. In one embodiment magnetic nanoparticles are injected into a breast and the lymph nodes collecting the particles are detected with the probe and deemed sentinel nodes.

20 Claims, 4 Drawing Sheets



(51)	Int. Cl.		7,009,398 B2	3/2006	Hahn et al.
	<i>A61B 5/00</i>	(2006.01)	7,044,957 B2	5/2006	Foerster et al.
	<i>A61B 5/06</i>	(2006.01)	7,084,631 B2	8/2006	Qu et al.
	<i>A61K 49/18</i>	(2006.01)	7,116,094 B2	10/2006	Levin et al.
	<i>B82Y 5/00</i>	(2011.01)	7,229,417 B2	6/2007	Foerster et al.
	<i>A61B 17/00</i>	(2006.01)	7,283,868 B2	10/2007	Ko et al.
			7,329,414 B2	2/2008	Fisher et al.
			7,335,511 B2	2/2008	Mountford et al.
(52)	U.S. Cl.		7,386,338 B2	6/2008	Hoppel et al.
	CPC	<i>A61B 5/418</i> (2013.01); <i>A61B 5/4312</i>	7,412,275 B2	8/2008	Marinelli
		(2013.01); <i>A61K 49/1863</i> (2013.01); <i>B82Y</i>	7,416,533 B2	8/2008	Gellman et al.
		<i>5/00</i> (2013.01); <i>A61B 2017/00876</i> (2013.01);	7,479,784 B2	1/2009	Lee
		<i>A61B 2562/12</i> (2013.01)	7,525,308 B2	4/2009	Tsukada et al.
			7,535,363 B2	5/2009	Gisselberg et al.
(58)	Field of Classification Search		7,570,056 B2	8/2009	Nakabayashi et al.
	CPC	<i>A61B 2017/00876</i> ; <i>A61B 2562/12</i> ; <i>A61K</i>	7,625,397 B2	12/2009	Foerster et al.
		<i>49/1863</i> ; <i>B82Y 5/00</i>	7,668,582 B2	2/2010	Sirimanne et al.
	See application file for complete search history.		7,676,256 B2	3/2010	Satragno et al.
			7,680,524 B2	3/2010	Ogawa et al.
			7,689,267 B2	3/2010	Prince
(56)	References Cited		7,701,209 B1	4/2010	Green
	U.S. PATENT DOCUMENTS		7,702,378 B2	4/2010	Bolan et al.
			7,711,407 B2	5/2010	Hughes et al.
			7,744,852 B2	6/2010	Chernomorsky et al.
			7,783,336 B2	8/2010	Macfarlane et al.
	3,449,662 A	6/1969 Wood	7,792,569 B2	9/2010	Burbank et al.
	4,324,255 A	4/1982 Barach et al.	7,877,133 B2	1/2011	Burbank et al.
	4,825,162 A	4/1989 Roemer et al.	7,972,619 B2	7/2011	Fisher
	4,983,912 A	1/1991 Roehrlein et al.	8,050,742 B2	11/2011	Weizman
	5,005,001 A	4/1991 Cordery	8,060,183 B2	11/2011	Leopold et al.
	5,184,070 A	2/1993 Besendorfer et al.	8,062,215 B2	11/2011	Voegele et al.
	5,261,403 A	11/1993 Saito et al.	8,064,987 B2	11/2011	Carr, Jr.
	5,293,119 A	3/1994 Podney	8,118,754 B1	2/2012	Flynn et al.
	5,363,845 A	11/1994 Chowdhury et al.	8,137,320 B2	3/2012	Mark et al.
	5,402,094 A	3/1995 Enge	8,174,259 B2	5/2012	Hattersley et al.
	5,414,356 A	5/1995 Yoshimura et al.	8,219,182 B2	7/2012	Burbank et al.
	5,416,413 A	5/1995 Leussier	8,277,391 B2	10/2012	Foerster et al.
	5,437,280 A	8/1995 Hussman	8,280,486 B2	10/2012	Miller et al.
	5,512,821 A	4/1996 Ando et al.	2001/0011155 A1	8/2001	Rapoport
	5,534,778 A	7/1996 Loos et al.	2001/0012915 A1	8/2001	Avrin et al.
	5,537,037 A	7/1996 Otaka et al.	2001/0049481 A1	12/2001	Fulton, III et al.
	5,657,756 A	8/1997 Vrba et al.	2002/0019595 A1	2/2002	Osborne et al.
	5,666,052 A	9/1997 Sata	2002/0035324 A1	3/2002	Sirimanne et al.
	5,844,140 A	12/1998 Seale	2002/0161298 A1	10/2002	Burbank et al.
	5,942,209 A	8/1999 Leavitt et al.	2003/0016010 A1	1/2003	Kandori et al.
	5,997,473 A	11/1999 Taniguchi et al.	2003/0078493 A1	4/2003	Ogawa et al.
	6,076,008 A	6/2000 Bucholz	2003/0141868 A1	7/2003	Bakharev
	6,082,366 A	7/2000 Andrä et al.	2003/0214313 A1	11/2003	Omura et al.
	6,173,715 B1	1/2001 Sinanan et al.	2003/0216632 A1	11/2003	McClure et al.
	6,205,352 B1	3/2001 Carroll	2004/0109823 A1	6/2004	Kaplan
	6,230,038 B1	5/2001 von Gutfeld et al.	2004/0162477 A1	8/2004	Okamura et al.
	6,270,464 B1	8/2001 Fulton, III et al.	2004/0236213 A1	11/2004	Jones et al.
	6,304,075 B1	10/2001 von Schaewen et al.	2004/0249261 A1	12/2004	Torchia et al.
	6,347,241 B2	2/2002 Burbank et al.	2005/0033157 A1	2/2005	Klein et al.
	6,356,782 B1	3/2002 Sirimanne et al.	2005/0059881 A1	3/2005	Balaban et al.
	6,371,904 B1	4/2002 Sirimanne et al.	2005/0148863 A1	7/2005	Okamura et al.
	6,394,965 B1	5/2002 Klein	2006/0074295 A1	4/2006	Kucharczyk et al.
	6,406,420 B1	6/2002 McCarthy et al.	2006/0173283 A1	8/2006	Axelsson et al.
	6,418,335 B2	7/2002 Avrin et al.	2006/0258933 A1	11/2006	Ellis et al.
	6,427,081 B1	7/2002 Burbank et al.	2006/0270930 A1	11/2006	Brasile
	6,445,185 B1	9/2002 Damadian et al.	2006/0293581 A1	12/2006	Piewes
	6,549,800 B1	4/2003 Atalar et al.	2007/0093726 A1	4/2007	Leopold et al.
	6,592,608 B2	7/2003 Fisher et al.	2008/0074109 A1	3/2008	Tsukada et al.
	6,603,308 B2	8/2003 Itozaki et al.	2008/0097199 A1	4/2008	Mullen
	6,638,913 B1	10/2003 Speck et al.	2008/0146914 A1	6/2008	Polzin et al.
	6,662,040 B1	12/2003 Henrichs et al.	2008/0161848 A1	7/2008	Fisher
	6,662,041 B2	12/2003 Burbank et al.	2008/0214930 A1	9/2008	Brasile
	6,699,205 B2	3/2004 Fulton, III et al.	2008/0228164 A1	9/2008	Nicoson et al.
	6,725,083 B1	4/2004 Burbank et al.	2008/0275333 A1	11/2008	Fain et al.
	6,766,186 B1	7/2004 Hoyns et al.	2008/0294036 A1	11/2008	Hoi et al.
	6,815,949 B2	11/2004 Kandori et al.	2009/0024022 A1	1/2009	Azar et al.
	6,835,572 B1	12/2004 Mountford et al.	2009/0082662 A1	5/2009	Israel
	6,836,118 B2	12/2004 Molyneaux et al.	2009/0118611 A1	5/2009	He
	6,850,065 B1	2/2005 Fujita et al.	2009/0164161 A1	6/2009	Hong et al.
	6,862,470 B2	3/2005 Burbank et al.	2009/0201016 A1	8/2009	Hattersley et al.
	6,889,073 B2	5/2005 Lampman et al.	2010/0030149 A1	2/2010	Carr, Jr.
	6,920,346 B2	7/2005 Kazandjian et al.	2010/0099978 A1	4/2010	Geppert et al.
	6,949,926 B2	9/2005 Murakami et al.	2010/0125191 A1	5/2010	Sahin
	6,963,769 B1	11/2005 Balaban et al.	2010/0305430 A1	12/2010	Troesken
	6,996,433 B2	2/2006 Burbank et al.			

(56)

References Cited

U.S. PATENT DOCUMENTS

2011/0021888 A1 1/2011 Sing et al.
 2011/0133730 A1 6/2011 Hattersley
 2011/0137154 A1 6/2011 Hattersley et al.
 2012/0229130 A1 9/2012 Hattersley et al.

FOREIGN PATENT DOCUMENTS

EP	0126580	11/1984	
EP	0595227	5/1994	
EP	0663599	5/1994	
EP	0966924	5/1997	
EP	1249207	10/2002	
EP	1062911	8/2003	
EP	1284123	7/2005	
EP	1491147	3/2010	
EP	2267471	12/2010	
EP	2339343	6/2011	
FR	2689638	10/1993	
FR	2770779	5/1999	
GB	2109112	5/1983	
GB	2425610	1/2006	
JP	02-078983	11/1990	
JP	02-281170	11/1990	
JP	05-251774	9/1993	
JP	06-324021	11/1994	
JP	08-015229	1/1996	
JP	08-248004	9/1996	
JP	08-338864	12/1996	
JP	10-038854	2/1998	
JP	2003-149212	5/2003	
JP	2005-168678	6/2005	
JP	2006-030004	2/2006	
JP	09-027057	8/2014	
WO	1995004287	2/1995	
WO	9807052	2/1998	
WO	2000038579	7/2000	
WO	2002039917	5/2002	
WO	2005011512	2/2005	
WO	2006009048	1/2006	
WO	2006056739	6/2006	
WO	2006117530	11/2006	
WO	WO-2006117530	A2 * 11/2006 G01R 33/1215
WO	2007034196	3/2007	
WO	2007053533	5/2007	
WO	2011033306	3/2011	
WO	2011067576	6/2011	
WO	2014013235	1/2014	

OTHER PUBLICATIONS

Jakub et al., "Current Status of Radioactive Seed for Localization of Non Palpable Breast Lesions", *The American Journal of Surgery*, vol. 199, No. 4, Apr. 2010, pp. 522-528.
 Meenach, "Synthesis and Characterization of Magnetic Hydrogel Nanocomposites for Cancer Therapy Applications", Doctoral Dissertations, paper 108, 2010, http://uknowledge.uky.edu/gradschool_diss/108.
 Postma et al., "Localization of Nonpalpable Breast Lesions", *Expert Rev. Anticancer Ther.*, vol. 11, No. 8, 2011, pp. 1295-1302.

Reddy et al., "Preparation & Application of Magnetic Hydrogel Nanocomposites for Protein Purification and Metal Absorption", International conference on Advances in Polymer Technology, Feb. 26-27, 2010, India, pp. 83-97.
 Freitas, Jr., "Nanomedicine, vol. I: Basic Capabilities", www.nanomedicine.com/NMI/8.2.1.2.htm, Landes Bioscience, Georgetown, TX, 1999, 4 pages.
 PCT International Search Report and PCT Written Opinion of International Searching Authority for International Patent Application No. PCT/GB2013/051885, dated Nov. 14, 2013, (18 pages).
 European Search Report for EP 10180206, dated Nov. 23, 2010, 4 pages.
 Material Safety Data Sheet; Revision Date Mar. 5, 2007; Retrieved from the Internet: URL:https://tools.lifetechnologies.com/content/sfs/msds/2007/11361D_VIAL1_MTR-NAIV_EN.pdf [retrieved on Jun. 10, 2014]; abstract; (6 pages).
 Harnan, S.E. et al.; "Magnetic resonance for assessment of axillary lymph node status in early breast cancer: A systematic review and meta-analysis"; *EJSO the Journal of Cancer Surgery*; 2011; vol. 37; pp. 928-936.
 Tsay, Tzong T. et al.; "Deep Cervical Lymph Flow Following the Infusion of Mannitol in Rabbits"; *Life Sciences*; 1997; vol. 61; No. 19; pp. 1929-1934.
 Williamson, S.J. et al.; "Biomagnetism"; *Journal of Magnetism and Magnetic Materials*; XP000574230; 1981; vol. 22; pp. 129-201.
 Fagaly, "Squid Detection of Electronic Circuits", *IEEE Transactions on Magnetics*, vol. 25, No. 2, Mar. 1989, pp. 1216-1218.
 Noguchi, et al., "Sentinel lymphadenectomy in breast cancer: identification of sentinel lymph node and detection of metastases," *Breast Cancer Research and Treatment*, vol. 53, 1999, pp. 97-104.
 Kim, et al., "Near-infrared fluorescent type II quantum dots for sentinel lymph node mapping," *Nat Biotechnol.*, vol. 22 (1), Jan. 2004, pp. 93-97.
 Gopee, et al., "Migration of Intradermally Injected Quantum Dots to Sentinel Organs in Mice," *Toxicological Sciences*, vol. 98(1), Apr. 2007, pp. 249-257.
 Soltesz, et al., "Intraoperative Sentinel Lymph Node Mapping of the Lung Using Near-Infrared Fluorescent Quantum Dots," *Ann Thorac. Surg.*, vol. 79(1), Jan. 2005, pp. 269-277 (reproduced from NIH Public Access).
 Peleg, et al., "Implementing metal detector technology and a navigation system in the removal of shrapnel," *Computer Aided Surgery*, Dec. 2009, vol. 14, No. 1-3; pp. 63-68.
 Conners, "Diagnostic uses of metal detectors: a review," *Int. J. Clin. Pract.*, Aug. 2005:59(8), pp. 946-949, Blackwell Publishing.
 Cash, et al., "Breast Cancers: Noninvasive Method of Preoperative Localization with Three-dimensional US and Surface Contour Mapping," Published online before print Sep. 21, 2007, doi: 10.1148/radiol.2452060906; Nov. 2007, *Radiology*, 245, 556-566 (downloaded on Sep. 28, 2011 from <http://radiology.rsna.org/content/245/2/556.full>).
 Peleg, et al., "Integration of computer-aided navigation and metal detector technology in the removal of shrapnel in terror attacks casualties," 7th Int. Conf. Computer-Aided Orthopaedic Surgery, Heidelberg, Germany, 2007 pp. 57-60.
 Gunasekera, et al., "Imaging applications of nanotechnology in cancer," *Targeted Oncology*, 2009, vol. 4, pp. 169-181.
 PCT International Search Report and Written Opinion of International Searching Authority for International Patent Application No. PCT/GB2010/002233, dated Mar. 16, 2011, 15 pages.

* cited by examiner

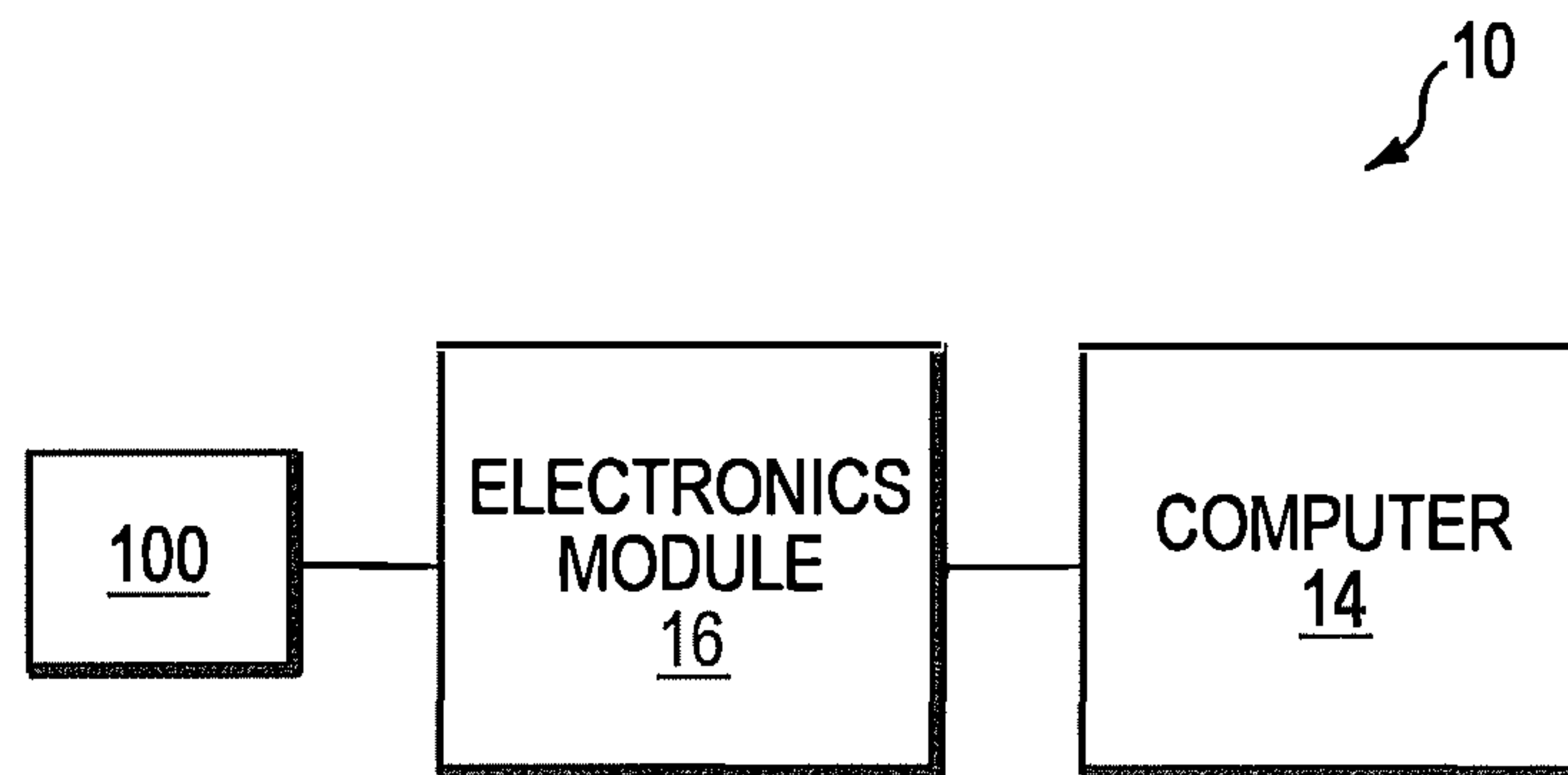


FIG. 1

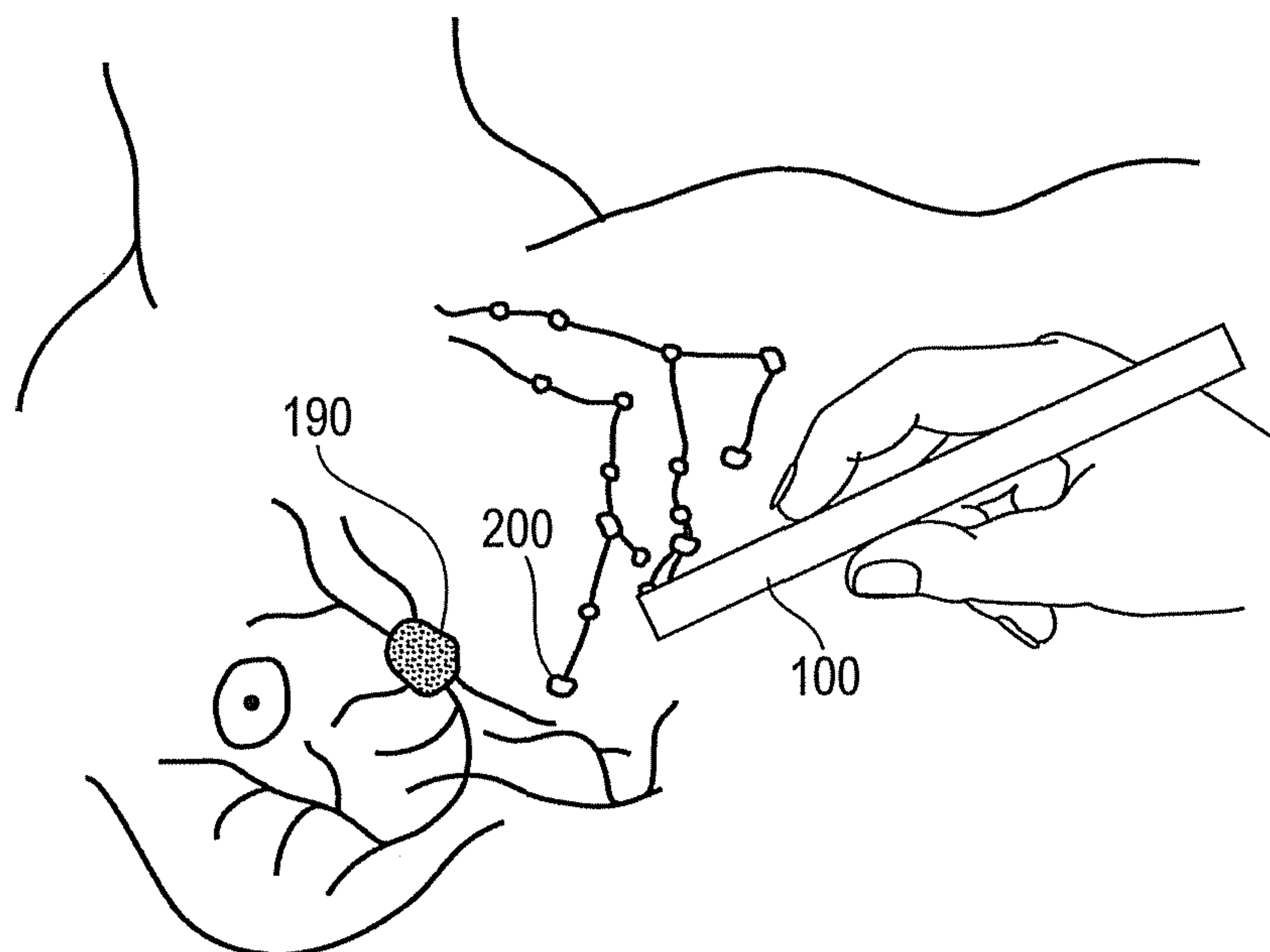
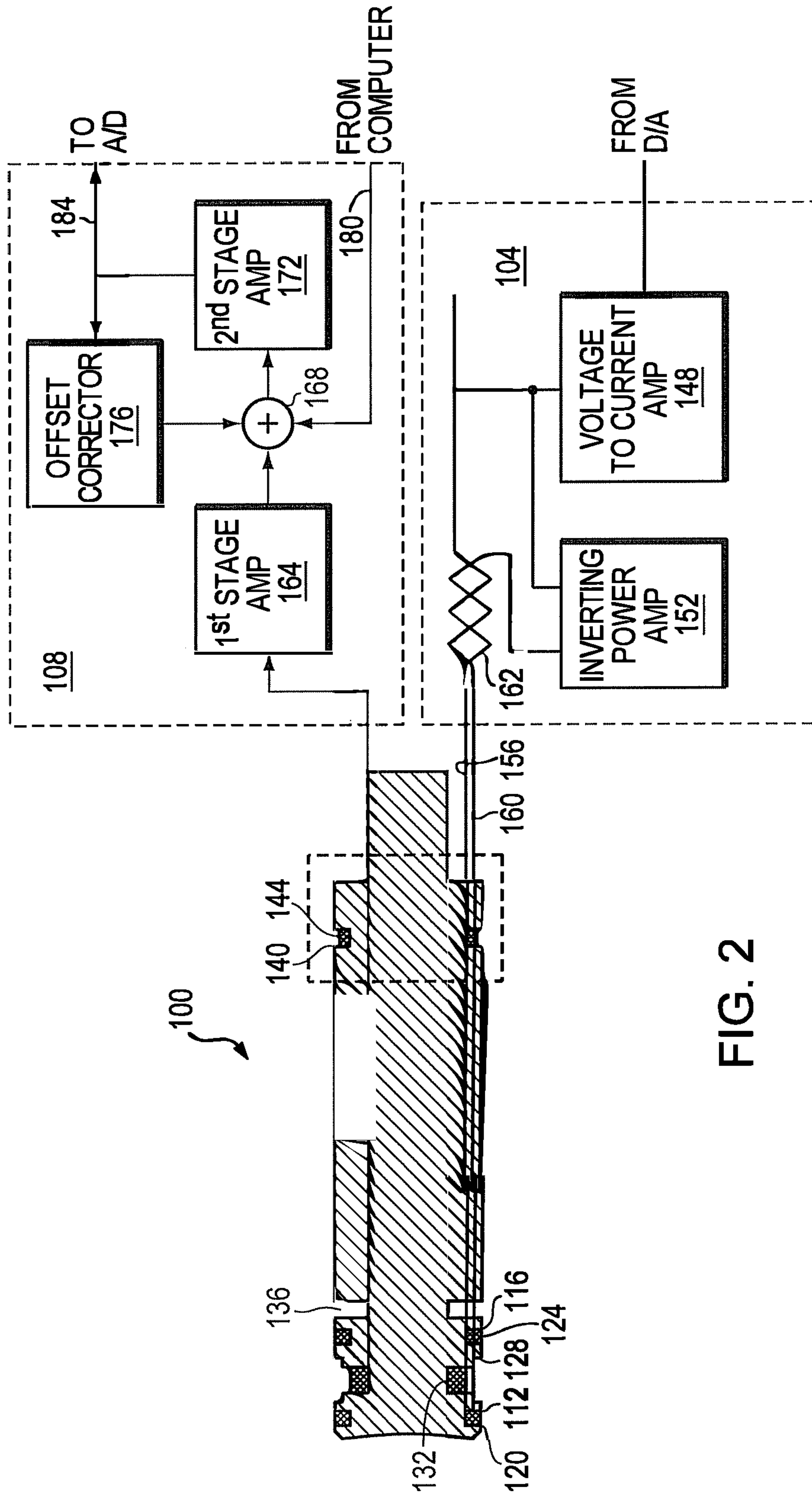


FIG. 4



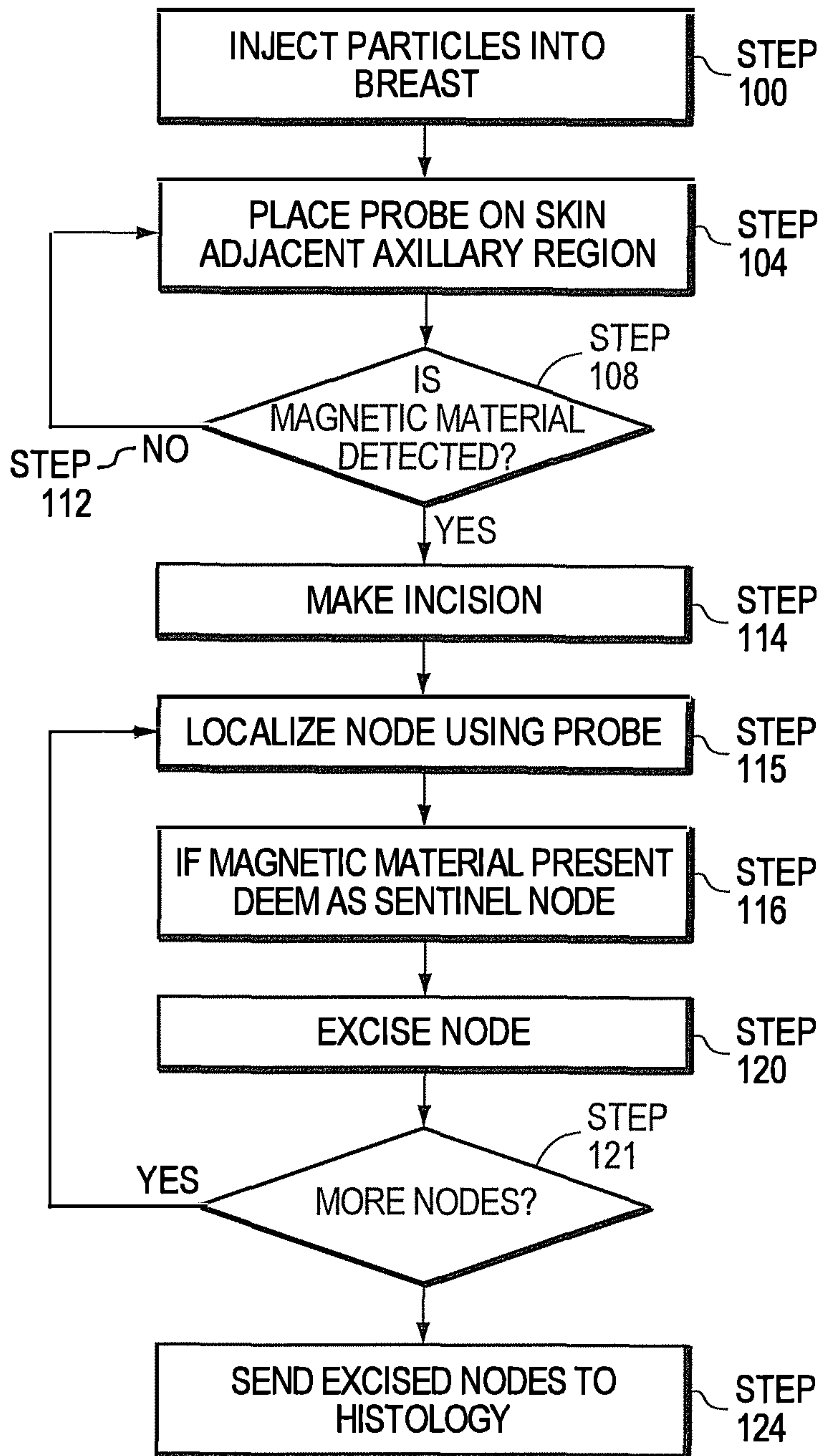


FIG. 3

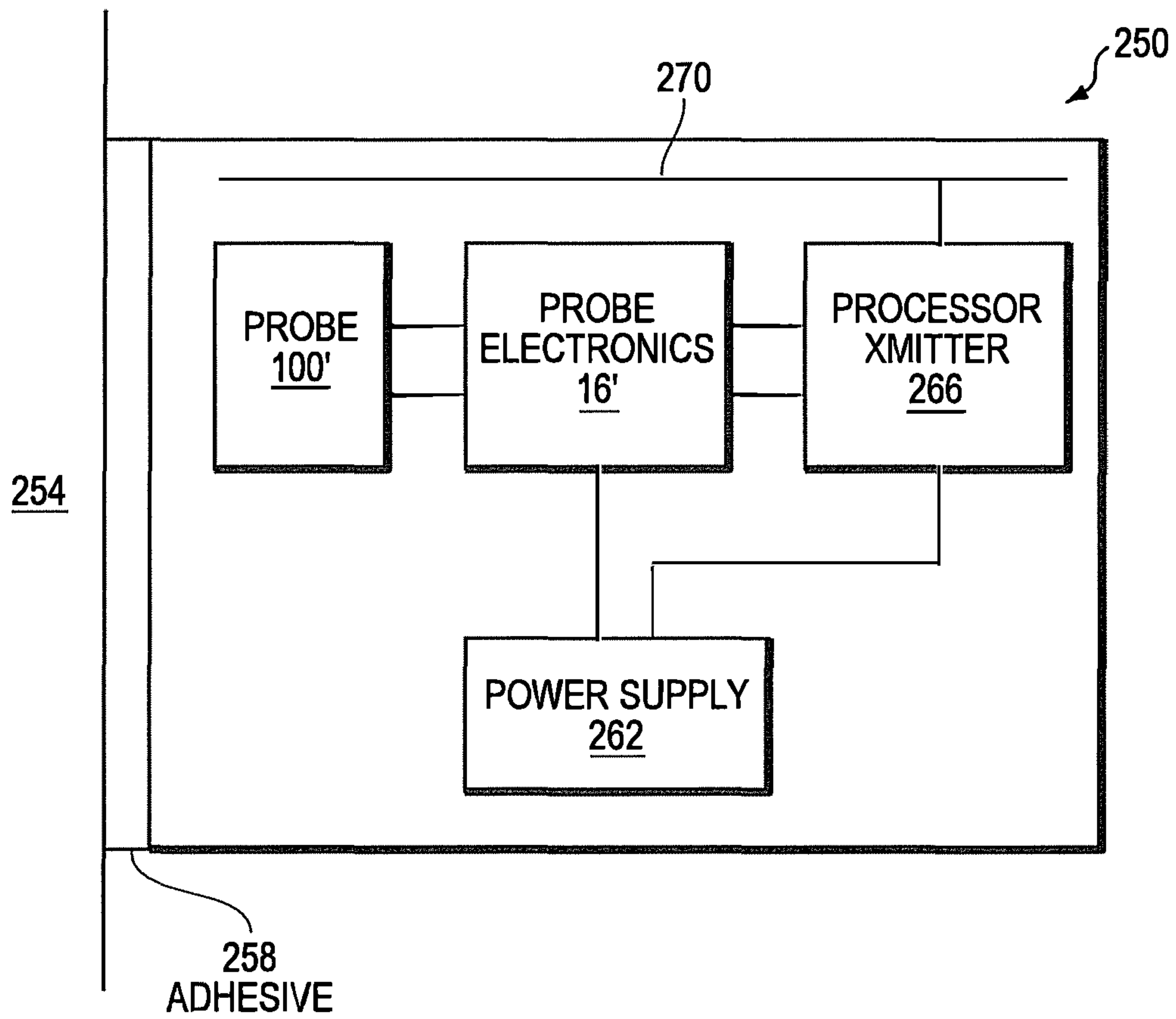


FIG. 5

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MAGNETIC PROBE APPARATUS**CROSS-REFERENCE TO RELATED APPLICATIONS**

This application is a continuation of U.S. patent application Ser. No. 12/631,370, filed on Dec. 4, 2009, the disclosure of which is herein incorporated by reference in its entirety.

FIELD OF INVENTION

This invention relates to the field of medical diagnostic devices and more specifically to a device to detect tissues of interest during a surgical procedure.

BACKGROUND

Approximately 1.25 million new cases of breast cancer are diagnosed each year. In a majority of these cases, there is an urgent need for surgery to remove the tumor and to excise the sentinel lymph nodes and inspect them histologically to determine whether the cancer has spread to other sites in the body. The sentinel lymph nodes are the first nodes to receive lymphatic drainage from the tumor. They are called this because they reliably alert the clinician to any cancer spread. A sentinel lymph node biopsy is a standard of care in breast cancer operations today.

Locating sentinel nodes during surgery is difficult. One method for locating the sentinel node is to inject a dark blue dye into the lymphatic system in the breast. The dye then disperses throughout the breast lymphatic system and the surgeon removes any colored nodes. This method is recognized as being error-prone.

An improved method involves injecting a radioactive dye into the lymph nodes. In a similar manner, the dye drains through the lymphatic system and the surgeon then uses a radiation detector to help locate the sentinel nodes. However, the use of radioisotopes presents a significant, and an expensive, logistical burden, because of the need to allocate the time and resources of a nuclear medicine radiologist in addition to the surgeon for what is otherwise a routine operation. Further many patients are reluctant to receive a radioactive injection. These factors become a significant barrier to the widespread adoption of the use of radioisotopes to locate the sentinel nodes.

The present invention overcomes these issues.

SUMMARY OF THE INVENTION

The present invention radically alters the sentinel lymph node protocol through the use of a detection system based on magnetism rather than radiation. The present system combines the magnetic properties of a magnetic nanoparticle suspension with a detector that is significantly more sensitive than other methods that can be used in the environment of an operating theater. In one embodiment the nanoparticles suspension is an FDA approved MRI contrast agent. Although in one embodiment the present invention is directed to locating sentinel lymph nodes, it can be used to detect other magnetic materials both within a body and in other environments.

In one aspect the invention relates to a system for locating magnetic material. In one embodiment the system includes a magnetic probe; a power module in electrical communication with the magnetic probe to supply current to the magnetic probe; a sense module in electrical communication

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with the magnetic probe to receive signals from the magnetic probe; and a computer in electrical communication with the power module and the sense module. The computer generates a waveform that controls the supply of current from the power module and receives a signal from the sense module that indicates the position of magnetic material. The magnetic probe is constructed from a material having a coefficient of thermal expansion of substantially $10^{-6}/^{\circ}\text{C}$. or less and a Young's modulus of substantially 50 GPa or more.

In one embodiment the magnetic probe comprises two concentric drive coils positioned on respective sides of a concentric sense coil. The two concentric drive coils are constructed so as to produce a zero magnetic field at the center of the sense coil. In another embodiment the magnetic probe further comprises an optional sense coil positioned away from the drive coils and constructed so as to cancel the ambient magnetic field effects in the sense coil. In yet another embodiment the probe is cylindrical and the drive and sense coils are positioned within respective circumferential grooves in the cylindrical magnetic probe. In still yet another embodiment an additional circumferential groove is constructed in the cylinder to reduce heat conduction.

In another embodiment the magnetic probe comprises two concentric sense coils positioned on respective sides of a concentric drive coil. The two concentric sense coils are constructed so as to produce equal and opposite currents in response to the magnetic field generated by the drive coil.

In another aspect the invention relates to a magnetic probe comprising a probe body having a first end and a second end. The probe body is sized to fit in the hand of a user and comprises a material having a coefficient of thermal expansion less than or equal to $10^{-6}/^{\circ}\text{C}$. and a Young's modulus of substantially 50 GPa or greater. A sense coil is positioned near the first end of the probe body, and two concentric drive coils are positioned concentric with and on respective sides of the sense coil. The two concentric drive coils are constructed so as to produce a zero magnetic field at the center of the sense coil. In one embodiment the magnetic probe further comprises an optional sense coil positioned away from the drive coils and constructed so as to cancel ambient field effects in the sense coil. In another embodiment the probe is cylindrical and the drive and sense coils are positioned within respective circumferential grooves in the cylindrical magnetic probe. In yet another embodiment an additional circumferential groove is constructed in the cylinder to reduce heat conduction.

In yet another aspect, the invention relates to a magnetic probe comprising a probe body having a first end and a second end. The probe body is sized to fit in the hand of a user and comprises a material having a coefficient of thermal expansion less than or equal to $10^{-6}/^{\circ}\text{C}$. and a Young's modulus of substantially 50 GPa or greater. A drive coil is positioned near the first end of the probe body and two concentric sense coils are positioned concentric with and on respective sides of the drive coil. The two concentric sense coils are constructed so as to produce equal and opposite currents in response to the magnetic field generated by the drive coil.

In one embodiment the magnetic probe further comprises an optional sense coil positioned away from the drive coils and constructed so as to cancel ambient magnetic field effects in the sense coil. In another embodiment the probe is cylindrical and the drive and sense coils are positioned within respective circumferential grooves in the cylindrical magnetic probe. In yet another embodiment an additional circumferential groove is constructed in the cylinder to reduce heat conduction.

Still yet another aspect of the invention relates to a system for detecting sentinel nodes in a breast lymph system. In one embodiment the apparatus comprises a magnetic probe; a power module in electrical communication with the magnetic probe to supply current to the magnetic probe; a sense module in electrical communication with the magnetic probe to receive signals from the magnetic probe; and a computer in electrical communication with the power module and the sense module. The computer generates a waveform that controls the supply of current from the power module to the magnetic probe and receives a signal from the sense module that indicates the position of a magnetic particle in the lymph system. The magnetic probe is constructed from a material having a coefficient of thermal expansion less than or equal to $10^{-6}/^{\circ}\text{C}$. and a Young's modulus of substantially 50 GPa or greater.

In one embodiment the magnetic probe comprises two concentric drive coils positioned on respective sides of a concentric sense coil. The two concentric drive coils are constructed so as to produce a zero magnetic field at the center of the sense coil. In another embodiment the magnetic probe further comprises an optional sense coil positioned away from the drive coils and constructed so as to cancel ambient magnetic field effects in the sense coil. In yet another embodiment the probe is cylindrical and the drive and sense coils are positioned within respective circumferential grooves in the cylindrical magnetic probe. In still yet another embodiment an additional circumferential groove is constructed in the cylinder to reduce heat conduction. In another embodiment the magnetic probe comprises two concentric sense coils positioned on respective sides of a concentric drive coil and wherein the two concentric sense coils are constructed so as to produce equal and opposite currents in response to the magnetic field generated by the drive coil.

In another aspect the invention relates to a magnetic probe including a pair of drive coils and a sense coil. The pair of drive coils and sense coil have different radii. The spacing between the drive coils and the sense coil is such that the rate of change of their mutual inductance with respect to the radius of the larger coil is substantially zero.

In another aspect the invention relates to a magnetic probe magnetic probe having a pair of sense coils, and a drive coil. The pair of sense coils and drive coil have different radii. The spacing between the drive coil and the sense coils is such that the rate of change of their mutual inductance with respect to the radius of the larger coil is substantially zero.

In yet another aspect the invention relates to a method for constructing magnetic probe. The method includes the steps of providing a pair of first coils, and providing a second coil, the pair of first coils and the second coil having different radii, and placing the pair of first coils and the second coil in the probe such that the spacing between the first coils and the second coil is such that the rate of change of their mutual inductance with respect to the radius of the larger coil is substantially zero.

In another aspect the invention relates to a method for detecting sentinel nodes in a breast lymphatic system. In one embodiment the method comprises the steps of: injecting a suspension of magnetic nanoparticles into the tissue of the breast; and scanning the axillary lymph nodes in the armpit, on the same side as the breast, with a magnetic probe. The magnetic probe includes a probe body having a first end and a second end. The probe body is sized to fit in the hand of a user and includes a material having a coefficient of thermal expansion less than or equal to $10^{-6}/^{\circ}\text{C}$. and a Young's modulus of substantially 50 GPa or more. A sense coil is

positioned near the first end of the probe body and two concentric drive coils positioned concentric with and on respective sides of the sense coil. The two concentric drive coils are constructed so as to produce a zero magnetic field at the center of the sense coil. In one embodiment the magnetic injection is a suspension of magnetic particles. In another embodiment the type of magnetic nanoparticle is a ferum oxide.

BRIEF DESCRIPTION OF THE DRAWINGS

The objects and features of the invention can be better understood with reference to the drawings described below. The drawings are not necessarily drawn to scale; emphasis is instead being placed on illustrating the principles of the invention. In the drawings, numerals are used to indicate specific parts throughout the various views. The drawings associated with the disclosure are addressed on an individual basis within the disclosure as they are introduced.

FIG. 1 is a block diagram of an embodiment of a system constructed in accordance with the invention;

FIG. 2 is a schematic diagram of the probe and electronic components of the embodiment of the system of the system shown in FIG. 1;

FIG. 3 is a flow diagram of an embodiment the method of determining the sentinel nodes utilizing the invention;

FIG. 4 is a drawing of the probe of the system being used to locate a sentinel node; and

FIG. 5 is a block diagram of another embodiment of the system constructed for wireless use.

DETAILED DESCRIPTION

The following description refers to the accompanying drawings that illustrate certain embodiments of the invention. Other embodiments are possible and modifications may be made to the embodiments without departing from the spirit and scope of the invention. Therefore, the following detailed description is not meant to limit the invention. Rather, the scope of the invention is defined by the appended claims.

Referring to FIG. 1, in brief overview, a system constructed in accordance with the teachings of the invention includes a computer **14** having a processor, RAM memory, long term data storage, input/output devices and display; an electronic module **16** containing the power and sensor electronics for the probe and the probe itself **100**. In one embodiment the input/output devices include a digital to analog converter and an analog to digital converter.

To maintain the stability of the system, it is necessary in part to provide thermal stability in the probe. This is done with a combination of a material having a combination of low thermal expansion and a high resistance to deformation with a careful positioning of the coils of the probe. Referring to FIG. 2, an embodiment of the electronics and probe components of the system of the invention includes the probe **100**, a drive circuit **104** and a sense circuit **108**. The probe **100** is generally a cylindrically shaped device sized to fit the hand of a user. In one embodiment the cylinder is about 75 mm long and 20 mm in diameter. In one embodiment the cylinder is made of Zerodur®, (Schott AG, Mainz, Germany) which is an inorganic, non-porous glass ceramic that has a non-directional, isotropic structure. During formation, this glass ceramic is subjected to thermal cycling which converts about 75% of the vitreous material into

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crystalline quartz. The resulting glass and crystal phases within the material balance such that the thermal expansion coefficient of one form of Zerodur® is of the order $0.02 \times 10^{-6}/^\circ\text{C}$. The substantially zero coefficient of expansion maintains the mechanical stability of the probe **100** over a wide temperature range. In addition the glass ceramic material is very stiff having a Young's modulus of 90 GPa. Other materials with coefficients of thermal expansion and Young's modulus similar to this material may also be used.

In one embodiment two grooves **112** and **116** are circumferentially formed near the first end of the cylinder body and two substantially identically sized coils of wire **120**, **124** are wound in the grooves. A third groove **128** is also formed in the cylinder substantially midway between and coaxial with the first **112** and second **116** grooves and a third coil **132** wound in that groove **128**. In this embodiment the depth of the third groove **128** is such that the outer surface of the third coil **132** is located at the same depth as the bottom of the first **112** and second **116** grooves and the groove **128** is wider than the other two grooves. In one embodiment the first **120** and second **124** coils are about 2 mm wide; have an inner radius of about 8 mm; and have about 48 turns of wire. The third coil **132** is about 3 mm wide; has an inner radius of about 5 mm and contains about 72 turns of wire.

The size of the coils and their placement relative to each other is selected so that as the coils change shape because of heating, their inductive change is minimized. Unfortunately there are presently no available electrical conductors with zero coefficient of thermal expansion. Tungsten wire offers an improvement over copper wire, reducing the coefficient by a factor of four, but it also suffers from four times the resistivity. For the drive coils the higher resistivity causes increased self-heating, for sense coils the increased resistivity increases the noise, so in the embodiments shown tungsten was not used.

The problem of differential radial expansion of the coils cannot be addressed through material selection, but it can be handled by careful calculation of coil geometry. Consider the coupling (mutual inductance) between a pair of coaxial coils, one of which has a larger radius than the other. If the coils are close together, then the coupling is reduced as the larger coil expands. If the coils are far apart, the coupling increases as the larger coil expands. Thus it is evident that there is a separation at which the coupling is unaffected by small expansions of the larger coil.

With real coils of non-zero radius, length and thickness, the mutual inductance can be calculated numerically as an integral of order 6 over the two coil volumes. Assuming the radii are selected first, the required separation may be determined iteratively. The mutual inductance between two filamentary circuits *i* and *j* is given by the Neumann formula:

$$M_{ij} = \frac{\mu}{4\pi} \oint_{C_i} \oint_{C_j} \frac{ds_i \cdot ds_j}{|R_{ij}|}$$

where R_{ij} is the distance between elements ds_i and ds_j on circuits C_i and C_j and μ is the magnetic permeability of the material between the filamentary circuits, which for glass ceramics is typically very close to μ_0 , the permeability of free space.

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For volume-filling coaxial cylindrical coils, this equation becomes (in cylindrical polar coordinates (*r*, θ , *z*):

$$M_{ij} = \frac{\mu}{4\pi} N_i N_j \int_{r_{j0}}^{r_{j1}} \int_{r_{i0}}^{r_{i1}} \int_{z_{j0}}^{z_{j1}} \int_{z_{i0}}^{z_{i1}} \int_{-\pi}^{\pi} \int_{-\pi}^{\pi} \frac{\cos(\theta_i - \theta_j)}{|R_{ij}|} r_i d\theta_i r_j d\theta_j \frac{dz_i}{z_{i1} - z_{i0}} \frac{dz_j}{z_{j1} - z_{j0}} \frac{dr_i}{r_{i1} - r_{i0}} \frac{dr_j}{r_{j1} - r_{j0}}$$

where

$$|R_{ij}|^2 = r_i^2 + r_j^2 - 2r_i r_j \cos(\theta_i - \theta_j) + (z_i - z_j)^2$$

and where N_i , N_j are the number of turns on each coil. This equation assumes a uniform current distribution over the coil cross-section, which is valid for low frequency and small wire size so that the skin effect can be neglected.

Given axial symmetry, one integral reduces to the circumference of a circle, leaving the following formula to be integrated numerically:

$$M_{ij} = \mu N_i N_j \int_{r_{j0}}^{r_{j1}} \int_{r_{i0}}^{r_{i1}} \int_{z_{j0}}^{z_{j1}} \int_{z_{i0}}^{z_{i1}} r_i r_j \int_0^{\pi} \frac{\cos(\theta_j) d\theta_j}{\sqrt{r_i^2 + r_j^2 - 2r_i r_j \cos(\theta_j) + (z_i - z_j)^2}} \frac{dz_i}{z_{i1} - z_{i0}} \frac{dz_j}{z_{j1} - z_{j0}} \frac{dr_i}{r_{i1} - r_{i0}} \frac{dr_j}{r_{j1} - r_{j0}}$$

It should be understood that the coil coupling is only insensitive to variation in the size of the larger coil, not to variation in the size of the smaller coil. For this technique to be effective, it is therefore necessary that the smaller coil is the central coil within a first order gradiometer made from two equal larger coils. Any change in the radius of the centre coil is balanced by an equal change in coupling to the coils on either side of it. A change in radius of either larger coil is compensated by its correct positioning.

A fourth groove **136** is also formed in the cylinder to reduce the thermal conductivity of the cylinder in use and reduce the amount of any heat generated by the coils **120**, **124** from flowing along the cylinder causing a thermal asymmetry and thereby making the local environment of the two coils **120**, **124** different. Two longitudinal grooves (not shown) are also formed in the surface along the length of the cylinder to provide paths for the wire connections to the various coils.

An optional fifth groove **140** may be formed near the end of the cylinder away from the first groove **112**, and an optional fourth coil **144** formed in the groove **140**. In one embodiment, the fourth coil **144** is about 2 mm wide; has an inner radius of 8 mm and has about 32 turns of wire. Although the fourth coil **144** is larger than the third coil **132**, their area-turns are substantially matched.

In one embodiment the first **120** and second **124** coils are counter wound and connected in series such that when energized by a current, the magnetic fields they produce are substantially cancelled at the center of the third coil **132**. For the purposes of this discussion, unless otherwise stated, the first **120** and second **124** coils are referred to as the drive coils and the third coil **132** as the sense coil. Also the fourth optional coil **144** will also be referred to as an optional sense coil.

Power is supplied to the drive coils **120, 124** by the drive circuit **104**. The drive circuit includes a voltage to current amplifier **148** and an inverting power amplifier **152**. In one embodiment the computer **14** generates a sine wave of appropriate amplitude and frequency and the digital to analog converter within the computer generates an analog voltage from this generated sine wave. In one embodiment the frequency of the sine wave is 10 kHz. The voltage to current amplifier **148** converts that voltage to a current used to power the drive coils **120, 124** through one series connected conductor **156**. In one embodiment the current is 100 mA. The current return conductor **160** is connected to the output terminal of the inverting power amplifier whose input terminal is also connected to the output of the voltage to current amplifier **148**. This configuration produces a balanced +V on one side of the drive coils **120, 124** and -V on the other side of the drive coils **120, 124**.

The sense circuit **108** includes a first stage amplifier **164**, a summing junction **168**, a second stage amplifier **172**, and an offset correction circuit **176**. A signal received from the sense coil **132** is the input signal to the first stage sense amplifier **164**. In one embodiment this amplifier has a gain of 250. The output of the first stage gain amplifier **164** is one input to the summing junction **168**. The output of the summing junction **168** is the input to the second stage amplifier **172**. In one embodiment the second stage amplifier has a gain of 400. The output of the second stage amplifier **172** is the input to the offset correction circuit **176** and the input to the analog to digital converter (not shown) connected to the computer **14**.

The offset correction circuit **176** integrates the output of the second stage amplifier **172** and its output is a second input to the summing junction **168**. The output of the offset correction circuit **176** provides a feedback signal in response to a positive offset to generate a negative ramp signal.

The third input to the summing junction **168** is a software controlled balance signal **180**. This signal, which is generated by a second digital to analog converter (not shown) of the computer **10**, is the signal which compensates for any unbalance in the sense coils **120, 124**. To perform this compensation function the probe **100** is held pointing to open space. The computer **10** generates a compensating balance signal **180** and measures the change of amplitude and phase of the output signal **184**. The computer **10** then calculates the vector (amplitude and phase) for the balance signal **180** necessary to null the output signal **184**.

Thus the balancing process determines the balance phasor required to obtain a near-zero output from the system. Normally balancing starts with the existing value. When starting without a prior value it may be necessary to use a lower drive current initially to avoid saturating the input, and then repeat the balancing at the required drive current.

The system measures the response S_0 at the original balance setting B_0 , then adjusts the balance phasor by a small amount to B_1 and measures the new response S_1 . The coupling from the balance output to the detected input is defined by:

$$X = \frac{S_1 - S_0}{B_1 - B_0}$$

which is the rate of change of the response to balance and therefore the new balance is reached when:

$$B_2 = B_0 - \frac{S_0}{X}$$

Alternatively the computer **10** can generate a balance signal **180**, measure the output signal **184** and modify the balance signal **180** iteratively until the output signal **184** is nulled.

To reduce the noise in the system, the optional sense coil **144** is utilized. This coil **144** is positioned away from the drive coils **120, 124** and generally detects the magnetic flux in the operating room and not the magnetic flux from the drive coils **120**. This optional coil **144** can be connected in series with the sense coil **132** such that any ambient magnetic field will produce a current in the optional sense coil **144** that is in opposition to the current that is produced by the ambient magnetic field on the sense coil **132**, thereby canceling the effects of the ambient magnetic field on the probe **100**. It should be noted that when coils are configured to cancel the effects of other coils, the coils canceling each other may be counter wound, or connected in series with their input and output leads reversed.

Further, the functions of the drive coils **120, 124** and the sense coil **132** can be reversed. If this is done this forms an embodiment in which there are two sense coils **120, 124** connected in opposition and a drive coil **132** positioned between them. The sense coils **120, 124** are constructed such that the field of from the drive coil **132** produces a current in each of the sense coils **120, 124** that is equal and opposite to the current produced in the other sense coil **124, 120**. The optional sense coil **144** is not needed in this configuration.

To reduce the noise in the system, the power to the coils **120, 124** and the signals from the sense coil **132** to the sense electronics **108** are each conducted by a twisted quad microphone cable for improved magnetic field rejection. Further the two twisted quad cables are both embedded in a longitudinally flexible yet laterally stiff sheath which prevents the conductors from moving relative to one another.

The output signal **184** from the sense circuit **108** is digitized by the computer's **14** analog to digital converter to provide an output time series. This time series is correlated to the output series generated by the computer **14**.

In particular, detection of the magnetic particles involves correlating the sampled input waveform with two sinusoidal reference waveforms, one in phase with the drive and one in quadrature. The result is a phasor; a complex number giving the amplitude and phase of the probe response:

$$S = \frac{2 \sum_N C_i V_i}{N} + i \frac{2 \sum_N S_i V_i}{N}$$

where V_i is the sampled input voltage and C_i and S_i are sampled cosine and sine waves respectively, and the input is processed in sections of N samples.

It is possible to use the amplitude $|S|$ as the system indication, in which case both magnetic and conductive materials are detected, or to use the dot product with a discrimination phasor to detect only the magnetic component. This works because the eddy current induced in a conductive material is in quadrature with the applied field, while the magnetization of a magnetic material at low

frequency is in phase with the applied field. Thus the system can be used not only for detecting magnetic materials but also conductive materials.

As the probe **100** is positioned closer to a node with magnetic particles, the results are displayed, in one embodiment, as an audible sound of increasing frequency and a graphics display of counts proportional to the detected field.

Referring to FIG. 3, during a surgical operation, a surgeon injects (Step **100**) the breast with a suspension of magnetic nanoparticles near a tumor **190** (FIG. 4). In one embodiment the nanoparticles are those used as an MM contrast agent. Feridex® (Bayer HealthCare Pharmaceuticals, Montville, N.J.) or Endorem™ (Guerbet, Paris, France) are ferum oxides used generally as an MRI contrast agent which are suitable for the magnetic detection purpose.

After a period of time the suspension drains into the axillary lymphatic system on the same side as the breast. The surgeon then places (Step **104**, FIG. 3) the probe **100** on the surface of the skin, attempting to localize a lymph node **200** (FIG. 4) by determining if magnetic particles are detected (Step **108**). If not (Step **112**) the surgeon continues to search for a node by placing the probe **100** in another location on the surface of the skin and the process repeats. If a magnetic region is detected, the surgeon then makes an incision (Step **114**) and attempts to localize the node with magnetic particles using the probe (Step **115**). If the node has accumulated the magnetic nanoparticles, it is deemed (Step **116**) a sentinel node. The node is then excised (Step **120**). The surgeon then looks for additional nodes (Step **121**) which may also be sentinel nodes and when complete sends the excised nodes for histological examination for evidence of cancer (Step **124**).

Referring to FIG. 5, the system of the invention may be used to study the long term properties of magnetic materials either in a biological context or otherwise. In one embodiment the probe **100'** of the invention is reduced in size and rather than being held by a user is placed in a small capsule **250** that is attached to the object of interest **254** by an adhesive **258**. The capsule **250** also houses a power supply battery **262**, the probe electronics **16'**, a microprocessor and transmitter **266** and an antenna **270**. The output of the probe electronics **16'** is digitized by the microprocessor **266** and the data transmitted using the antenna **270** to a receiving computer system (not shown). This embodiment for example is useful in tracking the behavior of magnetic particles without requiring that the patient or object be tethered to the computer system **14** by wires.

It is to be understood that the figures and descriptions of the invention have been simplified to illustrate elements that are relevant for a clear understanding of the invention, while eliminating, for purposes of clarity, other elements. Those of ordinary skill in the art will recognize, however, that these and other elements may be desirable. However, because such elements are well known in the art, and because they do not facilitate a better understanding of the invention, a discussion of such elements is not provided herein. It should be appreciated that the figures are presented for illustrative purposes and not as construction drawings. Omitted details and modifications or alternative embodiments are within the purview of persons of ordinary skill in the art.

It can be appreciated that, in certain aspects of the invention, a single component may be replaced by multiple components, and multiple components may be replaced by a single component, to provide an element or structure or to perform a given function or functions. Except where such substitution would not be operative to practice certain

embodiments of the invention, such substitution is considered within the scope of the invention.

The examples presented herein are intended to illustrate potential and specific implementations of the invention. It can be appreciated that the examples are intended primarily for purposes of illustration of the invention for those skilled in the art. There may be variations to these diagrams or the operations described herein without departing from the spirit of the invention. For instance, in certain cases, method steps or operations may be performed or executed in differing order, or operations may be added, deleted or modified.

Furthermore, whereas particular embodiments of the invention have been described herein for the purpose of illustrating the invention and not for the purpose of limiting the same, it will be appreciated by those of ordinary skill in the art that numerous variations of the details, materials and arrangement of elements, steps, structures, and/or parts may be made within the principle and scope of the invention without departing from the invention as described in the claims.

Variations, modification, and other implementations of what is described herein will occur to those of ordinary skill in the art without departing from the spirit and scope of the invention as claimed. Accordingly, the invention is to be defined not by the preceding illustrative description, but instead by the spirit and scope of the following claims.

What is claimed is:

1. A probe comprising:

a handheld probe body comprising a first order gradiometer,
the first order gradiometer comprising a first drive coil having a first radius, a second drive coil having a second radius,
the handheld probe body having an axis, wherein the handheld probe body is cylindrically shaped; and
a sense coil positioned between the first drive coil and the second drive coil, the sense coil having a third radius, wherein the third radius is smaller than the first radius and the second radius, wherein the first drive coil, the second drive coil, and the sense coil are disposed along the axis of the handheld probe body, the sense coil centrally disposed between the first drive coil and the second drive coil,
wherein the first drive and the second drive coils are operable to produce magnetic fields which induce equal and opposite currents in the sense coil.

2. The probe of claim 1, wherein a change in radius of sense coil is balanced by an equal change in coupling of sense coil to first drive coil and second drive coil.

3. The probe of claim 1, wherein handheld probe body comprises a non-porous ceramic material.

4. The probe of claim 1, wherein an axial spacing between the first drive coil and the sense coil is such that while the first radius of the first drive coil and the third radius of the sense coil expand in response to heating change in mutual inductance between the sense coil and the first drive coil is inherently zero.

5. The probe of claim 1, wherein diameter of probe body is greater than diameter of each of the first drive coil, the second drive coil and the sense coil.

6. The probe of claim 1, wherein the probe is operable to detect magnetic nanoparticles or sentinel lymph nodes.

7. The probe of claim 1 further comprising:

a power module in electrical communication with one or more drive coils of the probe;

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a sense module in electrical communication with the probe to receive signals from the sense coil of the probe; and

a processing module in electrical communication with the power module and the sense module; wherein the processing module generates a waveform that controls the supply of current from the power module to the probe; wherein the processing module receives a signal from the sense module that indicates the proximity to magnetic nanoparticles and/or sentinel lymph nodes.

8. The probe of claim **1**, wherein the probe body has a coefficient of thermal expansion less than or equal to $10^{-6}/^{\circ}\text{C}$.

9. The probe of claim **1**, wherein the probe body has a Young's modulus of 50 GPa or greater.

10. The probe of claim **1**, wherein the first drive coil and the second drive coil are constructed to produce a zero magnetic field at the center of the sense coil.

11. The probe of claim **1**, wherein the first drive coil and the second drive coil are wound relative to the axis.

12. The probe of claim **11**, wherein the sense coil is wound relative to the axis.

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13. The probe of claim **1**, wherein one or more of the first drive coil, the second drive coil, and the sense coil are disposed in a groove defined by the probe body.

14. The probe of claim **13**, wherein the groove is a circumferential groove.

15. The probe of claim **1** further comprising one or more twisted quad cables.

16. The probe of claim **15**, wherein the one or more twisted quad cables are connected to and configured to power one or more of the first drive coil and/or the second drive coil.

17. The probe of claim **15**, wherein the one or more twisted quad cables are connected to and configured to receive signals from the sense coil.

18. The probe of claim **15**, wherein the one or more twisted quad cables are embedded in a longitudinally flexible yet laterally stiff sheath.

19. The probe of claim **1** further comprising a display in electrical communication with the sense coil.

20. The probe of claim **18** wherein the display is configured to display changes in detecting magnetic particles in a patient as position of the probe body changes.

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